Doctoral thesis (hereinafter referred to as "thesis"), title of the thesis:

Evolutionary Synthesis of Complex Digital Circuits

Name of the doctoral student (hereinafter referred to as "student"), name and surname:

Ing. Jitka Kocnová

Name and institution of the reviewer (full name of the reviewer, full name and country of the institution):

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Please state your opinion on the following aspects of (I) the student's thesis and (II) the student's overall achievements, and (III) state your conclusion (a minimum of approx. 300 characters foreach <u>item</u> below is recommended):

I. Thesis

<u>Appropriateness and relevance</u>

Is the area addressed by the thesis appropriate to the particular scientific discipline of the thesis and does the thesis address relevant problems within the chosen area?

The research area of the thesis sits at the centre of digital engineering, specifically looking at improving essential parts of digital electronic design automation (EDA) flows. As such, the thesis is entirely appropriate within the scientific disciplines of electronic engineering, information technology, computer systems, and computer science.

EDA tools are fundamental to the design and implementation of pretty much any digital electronic device, from integrated circuits (ICs) in washing machines, over medical devices and mobile phones, to cars and planes. Hence, any methodologies that can improve efficiency or performance of these systems are highly relevant for technology in the modern society.

Specifically, this thesis is looking at improving upon current methods of the process of circuit synthesis, which is the step where functional specifications are transformed into designs that can then be mapped and implemented in hardware. Optimisations at this stage of the EDA flow is crucial to achieve best possible performance and efficiency in the final IC product, further highlighting the relevance and timeliness of the research undertaken.

A summary of the contributions of the thesis

From your point of view, please summarize what the goal of the thesis is, what the main contributions of the thesis are, and whether the thesis has achieved the chosen goal. Please indicate also specific contributions of the student.

The overarching goal of the thesis is to develop an optimisation method to improve synthesised circuit netlists over what is currently achieved by state-of-the-art synthesis tools. Specifically, the aim is to reduce gate count using an evolutionary optimisation approach.

Based on this, the main hypothesis is formed: "Circuit resynthesis based on iterative sub-circuit selection and subsequent evolutionary optimization of every sub-circuit can achieve a significantly better gate reduction of the resulting circuit compared to the case where optimisation is applied to the whole circuit."

Following-on from the main hypothesis, several research objectives are stated:

1. To evaluate present conventional and evolutionary techniques of optimisation of digital circuits.
2. To propose various methods which extract sub-circuits suitable for the evolutionary optimisation.
3. To experimentally validate proposed methods using relevant set of circuits.
4. To modify the sub-circuit extraction methods to account for non-uniform delays at the inputs of the extracted sub-circuits.

Overall, the thesis has achieved the chosen goal stated in the hypothesis and the objectives. The main contributions of the student in her thesis thesis can be categorised as technical contributions, contributions to scientific body of knowledge, and new methodologies.

Technical:

- A tool that interfaces with an open-source EDA flow (ABC, Yosys), taking in tool-synthesised gate netlists, extracting cut-sets based on parameterizable settings, performing optimisation on them, and re-injecting the optimised results into the EDA flow.
- An evolutionary algorithm framework based on cartesian genetic programming (CGP) that can perform optimisations on the chosen cut sets while preserving compatibility with the overall netlist.
- A challenging and industry-relevant benchmark circuit suite has been successfully used to evaluate methods developed in this thesis.

Methodology:

- A divide-and-conquer approach based on cut sets to make more computationally expensive optimisation methods, e.g. evolutionary algorithms, viable for circuits with a large number of gates.
- Three different parameterizable algorithms for extracting cut-sets (subcircuits) from gate-level netlists and represent them in a data structure that allows further optimisation with custom tools.
- A method using a SAT solver in conjunction with a circuit simulator to increase efficiency of the costly candidate circuit evaluation during the optimisation process.

Science and knowledge:

- Divide-and-conquer approaches using subcircuit extraction and resynthesis can accelerate global circuit optimisation approaches based on evolutionary algorithms at the cost of convergence speed, hence, are more scalable.
- Evolutionary algorithms can outperform state-of-the-art approaches when optimising circuits globally at the cost of longer optimisation runtime.
- Cut set extraction based on reconvergent paths have a higher probability of successful gate reduction under circuit optimisation / resynthesis.

These findings and contributions are significant and warrant the award of a PhD.

Novelty and significance:

Please assess the level of novelty of the results and their significance for the given scientific area, for its further development, and if applicable for possible applications in practice.

Several of the contributions mentioned above are novel and all are significant in digital engineering of ICs. The main contributions in terms of novelty are the combination of cartesian genetic programming (CGP) and algorithms for cut set extraction for local resynthesis to achieve globally more optimal solutions and increase search efficiency / runtime of the evolutionary search. This approach is also significant in this research area, because it is known that evolutionary approaches are good global optimisers but are often not scalable and therefore not viable due to their prohibitively long runtime. Making this kind of global optimisation approaches more tractable is important, particularly at present since design targets are not solely focussed on timing, but also on circuit compactness, power requirements, and resource consumption. Experiments in the thesis successfully demonstrated that the proposed framework works, and that it can optimise gate count (circuit area) while not sacrificing timing (circuit speed). Hence, a straightforward extension of the outcomes of the thesis might be in reducing dynamic power consumption and leakage, which could easily be incorporated by introducing corresponding fitness metrics and including, for instance, high-threshold / low-threshold digital cells in the search.

The algorithms for cut-set extraction, specifically the approach using reconvergent paths constitutes a second significant novel contribution. This kind of algorithm is generically applicable and may be included in EDA tools, or other graph-orientated methods, independent of the framework of this thesis.

Evaluation of the formal aspects of the thesis:

Please evaluate formal qualities of thesis and its language level.

The thesis is comprised of an introduction, background, overall discussion of research outcomes, and conclusions and future work, as well as five first-author publications of the PhD candidate.

The structure of the thesis is clear, and standard for a PhD thesis of this format. The language and grammar are of very high standard.

The background chapter covers relevant research and methods that are necessary to understand the research undertaken in the thesis and the contributed papers. Citations and references are of good breadth and depth and are also relevant to the research presented.

In conclusion, the submitted document is of appropriate level and format as one might expect from a PhD thesis.

Quality of publications

Has the core of the thesis been published at an appropriate level? Please judge the quantity and quality of the publications. When judging the quality, please take into account internationally recognized standards (WoS/Scopus quartiles, CORE ranks, specific knowledge of flagship publication channels of agiven community, etc.) in a way appropriate for the given area of the thesis.

The candidate's list of publications is significant, with five publications representing the research forming the thesis, and a sixth additional paper. There is one journal paper in a very good international journal from the area of evolutionary computation and four conference publications, all published in high-ranking international conferences. In addition to the five papers forming this thesis, the author has authored or was involved in a further publication in an equally internationally acclaimed conference.

All core ideas and contributions of the thesis have been published and I consider the number and quality standard of the publications as sufficient to defend this doctoral dissertation.

II. Student's overall achievements

Overall R&D activities evaluation:

Does the student's thesis, the results included into it, and possible other scientific achievements listed in the list of scientific activities indicate that he/she is a person with scientific erudition and creative abilities?

Based on the thesis and publications presented, I am fully confident of the student's ability to carry out scientific investigations as an independent researcher. Each scientific paper contributed to the thesis is a piece of scientific enquiry, comprising of background, motivation, experiment design, results, and critical discussion. All papers taken together are then complimented by a chapter of critical analysis and appraisal of the overall outcomes of the thesis. Overall, these outputs and the methodology followed when undertaking research are worthy of the award of a PhD.

Assessment of other characteristics (optional):

More characteristics of the student may be added here (e.g., awards, grant participation, international collaboration, etc.).

One additional observation that may be made here is the fact that the candidate has been working in an EDA company doing digital design for the past several years, which may open pathways for impact for the research undertaken.

I am not private to whether the PhD has been undertaken part-time or not, but publications are coinciding with the time the candidate has been working in the company, which is also a great achievement.

III. Conclusion

The conclusion should contain an explicit statement saying whether, in your opinion, the thesis and the student´s achievements until now meet the generally accepted requirements for the award of an academic degree (in accordance with Section 47 of Act No. 111/1998 Coll., on higher education institution).

This is a well-written doctoral thesis presenting novel contributions and scientific results in the area of the use of evolutionary optimisation for design optimisation of large-scale digital circuits. In particular, it is impressive to see a scalable, effective, and flexible approach developed and integrated into an industry-relevant open source EDA design flow. It is great to see innovative and creative use of evolutionary computation to make this kind of global optimisation approach scalable.

In my professional opinion, Jitka Kocnová, the author of this thesis has proven her ability to independently conduct research and achieve original scientific results and critical appraisal worthy of a PhD. The thesis contains both new and original results that have already been published in high-quality international journals or conferences. Therefore, **I recommend the thesis for presentation and defence**.

York, UK - 21.05.2024

Signature of the reviewer: